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14. ABSTRACT
This STTR explores the details of designing a SAR type system that maps building interiors at close ranges with an entirely covert system. The program has defined a top level SAR operations parameter set, identified technical challenges specific to the Random Radar mission, and has delineated a design that meets those challenges. Wave propagation through buildings and their interiors has been characterized thoroughly. Near field SAR image formation equations, differing substantially from classical SAR image formation techniques, have been defined. Electromagnetic simulations that generate what the SAR receiver input signals would be for certain building scenarios were generated – from which SAR images were formed. The program also conducted a thorough radar systems architecture trade study and found one radar topology that fulfilled all radar system performance requirements where many radar system topologies fail.

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Contract FA9550-06-C-0118
STTR Program AF06-T024
Random Radar

STTR Project SUMMARY

16 November 2007

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EXECUTIVE SUMMARY

INTRODUCTION

This purpose of this STTR program "Random Radar" is to take the first steps in the development of a light weight system that will provide excellent images of structures and people interior to a building. A second key requirement of the system is that a sophisticated enemy will not be able to detect the system while it is in use, i.e. provide covert operation. Covertness is supported by both equipment disguise and the use of radiation levels that are unlikely to be detected – even by a well equipped adversary.

SYNTHETIC APERTURE RADAR (SAR) FOR BUILDING MAPPING

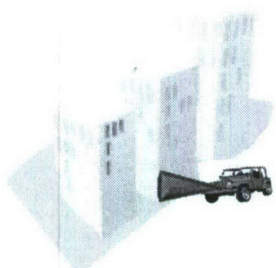


Figure 1. Buildings may be mapped by a small SAR system in a simple "drive by" scenario.

The system will make maps of the interior features of one or more buildings by using the SAR in a strip map mode. The radar will be mounted on the small vehicle and driven alongside the building(s) to be mapped at slow–to-moderate speeds (Figure 1). The program design baseline considers a vehicle speed of 20 mph.

After the "drive by," a map of the building scene, including building interiors, will be computed in near real time and made available to system operators.

The program bases its Synthetic Aperture Radar design on electromagnetic scattering analysis results developed by the Ohio State University. We use their state of the art electromagnetic wave propagation analysis capability to predict propagation losses through walls made of many different materials, predict the amplitude of high power echo signals (radar returns) from the first nearest wall, and to compute backscattered signals (both phase and amplitude) from the SAR signal source as would arrive at the SAR receive antenna from defined test scenes. The images formed from the SAR will have approximately 25 cm X 25 cm resolution, which is adequate to form a reasonably detailed SAR map of a building interior.

SYSTEM DESIGN

A baseline design has been developed during the course of the program that satisfies the needs of the application. It has good SAR mapping of buildings performance, and is indeed covert.

COVERT OPERATIONS

Interim report #1 presents an analysis showing that covert operations may be achieved through special transmitter techniques using either random or deterministic waveforms. A signal link budget (energy transfer analysis, report 1, table 1) indicated that system operation using these methods would show a human behind 5 building walls in the image map with + 6 dB SNR pixels. Using this transmit power with low gain antennas, report #1 determined that an adversary behind 5 walls with good receiver equipment could not detect the radar. The section below titled "Covert Methods" expands this discussion and shows a further example.

SYSTEM DESIGN CONCLUSION

The SET radar design selects a radar waveform and architecture that provides a high fidelity SAR image of building interiors in a timely fashion. This waveform in the described structure is the most advantageous waveform / architecture to use as it supports the special needs of the Random Radar mission.

SUMMARY

The Random Radar mission is unique and it generates a unique set of system performance requirements. The need to map building interiors at very short standoff ranges creates a special radar design challenge. Careful evaluation of all possible waveforms and radar receiver / exciter architectures has been conducted on this program which has yielded a viable design that is up to the challenge.

The selected architecture is optimum for short range radar, especially the Random Radar, offering the best slant range resolution for a given RF bandwidth in addition to other important features.

Numerous architectures other than the selected one were examined during this program; pertinent details of those examinations are given in the body of this summary. The baseline SAR system design is presented.

PROGRAM OBJECTIVE AND RESULTS SUMMARY

PROGRAM OBJECTIVES

ELECTROMAGNETIC SIMULATION OBJECTIVES

The objective of creating simulated radar data as collected by a radar receiver operating in the Random Radar application described above was accomplished by The Ohio State University's Electro-Science Laboratory (OSU-ESL). Numerous scenes of objects inside buildings were simulated and radar data for all these scenes was generated. Furthermore, OSU-ESL generated SAR images from the data as did SET. It was anticipated that substantial signal distortion due to multi-bounce, refraction, and inhomogeneous wave propagation velocities that occur inside buildings would greatly distort attempts to form SAR images without advanced correction techniques. SET proposes that correction algorithms to account for distortion effects should be vigorously pursued in the next phase of the program. That effort will potentially result in very crisp images as perceived by the untrained eye.

DETAILED RADAR SYSTEM PAPER DESIGN

Numerous radar system architectures and waveforms were thoroughly evaluated for applicability to the Random Radar mission. Conclusive results were obtained, as described above. The requirements combination of short range operation, and high range resolution (which requires wide RF bandwidth) eliminated many candidate radar designs.

A summary result is that construction of a practical, covert, effective building mapping SAR is not only feasible but may be accomplished without extraordinary cost or risk so long as the recommended radar architecture mentioned in the executive summary (and below) is adopted. That radar architecture is a best fit to the application by great measure. SET proposes to build such a covert SAR system on the next phase of development in accordance with the findings of this Phase I effort.

SPECIAL SYSTEM REQUIREMENTS

The special requirement of radar operations near large reflecting targets, such as a building, was analyzed and quantified at the beginning of the program. Also, the electromagnetic wave propagation losses through various wall materials was characterized. Completion of these analyses prior to radar system design assured that the ensuing radar system design activity had firm numerical requirements regarding operating frequency and over-all system sensitivity. These analyses were completed using OSU-ESL advanced electromagnetics wave scattering and propagation computational techniques, where radar echo signals as seen by the Random Radar receiver from various building scenes are computed. This analysis method allows complete characterization of backscattering from the building in the scene and propagation losses into the building interior.

WALL PROPAGATION LOSSES

The first analysis conducted was to characterize effective losses through building walls. Numerous wall constructions, wave incident angles, and scenes with combinations of different walls were studied, resulting in enough knowledge to support a responsive system design. Figure 2 summarizes the propagation study.

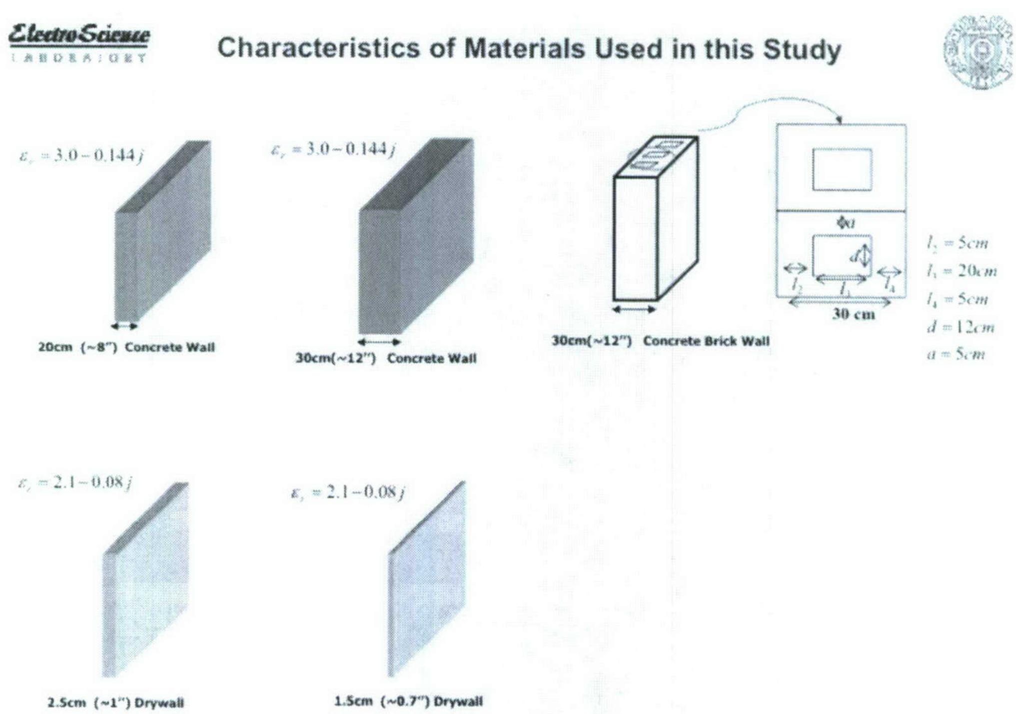


Figure 2. (a) Material properties descriptions. This thorough study provides data required by the system design activity.

Completion of the study outlined in figure 5 allowed radar system design to commence, since we at this point knew what round trip (radar to target to radar) attenuation factors to expect. We note that the 5 wall example has a range extent of 25 meters.

Radar link budget calculations determine how much transmit power is needed given a number of factors for any given scenario. In the link budget of this design (below), a one-way attenuation through 5 walls of appropriate value is used when operating over the selected frequency band.

SAR OPERATIONS FOR COVERT BUILDING MAPPING

The system design that results from the wall and materials propagation study shown above will be described in the next section from a top level operational view point, a link budget (power / energy transfer) analysis, and finally an assessment of the design for characteristics that support covert operations.

SAR OPERATIONAL PARAMETERS

As discussed in the program proposal and summarized in status report #1, the system concept of operations is to drive by one or more buildings with a small SAR bearing vehicle to map the building(s) interiors. The SAR designed parameters for strip map operation were computed on the program.

Use of appropriate platform velocities and coherent integration times produces a SAR image of such fidelity that a small target in the image at 25 meters building depth is clearly discernable. The total image size depends on the willingness of the project to add memory to the system processor, however images that are dozens of meters in length are envisioned as generated by a moderately sized processor assembly (desk-top computer size).

The specified operational scenario has benefits in that the platform doesn't move too slowly and time on target is kept low enough to support quick image formation. The short amount of time on target also promotes covert operations since the enemy has little time to discover the Random Radar signal presence. In order to achieve the operations timeline derived in the program analyses, and to achieve the required sensitivity to image small targets at 25 meters building depth, numerous specific radar parameter setting are required. These derived requirements will be of utmost importance in the waveform trade-off study given below.

COVERT METHODS

SET interprets the "covertness" requirement to mean that the Random Radar emissions will not be detected by the enemy under observation, or by his support groups which may be nearby.

SIGNAL INTERPRETABILITY VS. DETECTION

There is a view that if a signal is highly random like in nature or sufficiently complex, an enemy will not be able to interpret the signal, even though he may be able to detect such signal. It is

SET's position that regardless of the lack of interpretability of a signal, its mere detection defeats the covertness goal of the Random Radar program. Thus even though a signal may not be interpretable, it may not satisfy the covertness requirement of this Random Radar program.

In light of the discussion above, SET's design approach to achieve system covertness is to radiate waveforms with properties that make the radiated waveform extremely difficult to detect. Because SET believes that "covert" means not detectable, the interpretability of the waveform carries less weight because the enemy cannot observe it if the covert requirement is met.

Signal Detectability

To make an assessment as to the covertness of the proposed system, the power received in an enemy receiver from the Random Radar is calculated. A simple case study is shown in figure 3, where the enemy receiver is two rooms into the building interior.

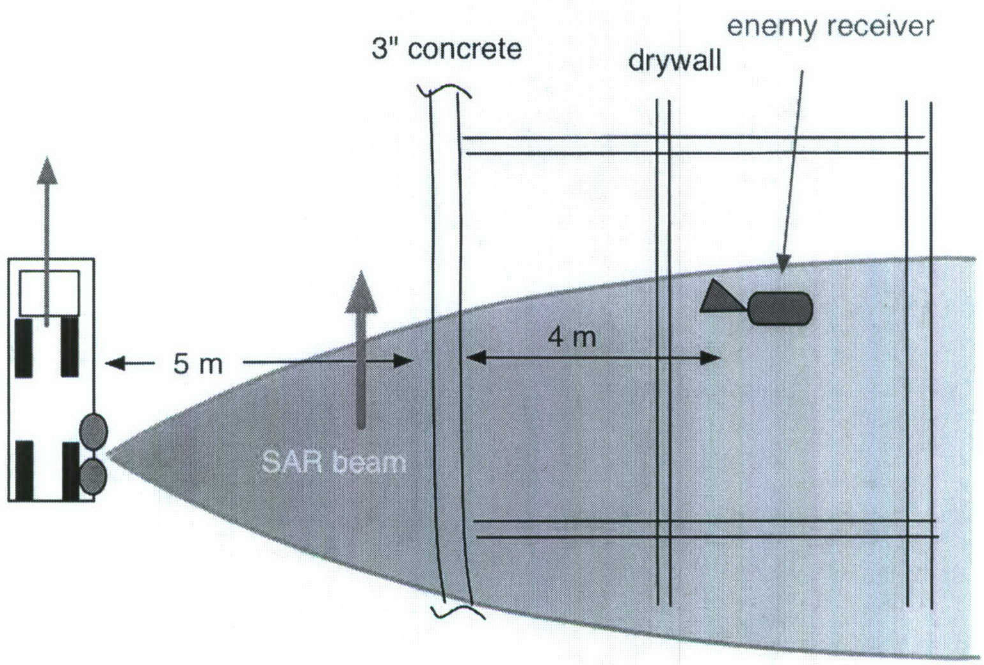


Figure 3. Enemy receiver placed two rooms into a building.

From the situation depicted in figure 3, we may calculate the amount of radiated power from the Random Radar as observed by the enemy receiver, given certain assumptions about the enemy receiver. The calculations were made during the program when the receiver is on the Random Radar antennas boresight.

Although the calculation has assumed a specific enemy receiver bandwidth for illustrative purposes, the calculation is essentially independent of receiver bandwidth since the input signal bandwidth is presumed to be much greater than the receiver bandwidth. In the example case, the

Random Radar is not detectable. Another important factor to consider is that the Random Radar beam will be present on the enemy receiver antenna for a limited time, making the Random Radar quite difficult to detect.

SYNTHETIC APERTURE RADAR IMAGE FORMATION

The Ohio State University used their electromagnetics propagation and scattering analysis methods to produce radar data from simple scenes as would be made by the Random Radar. That data was used to form images both at OSU and SET. The images take account of the fact that this SAR application is for very short ranges, thus "near field" SAR image formation methods are used.

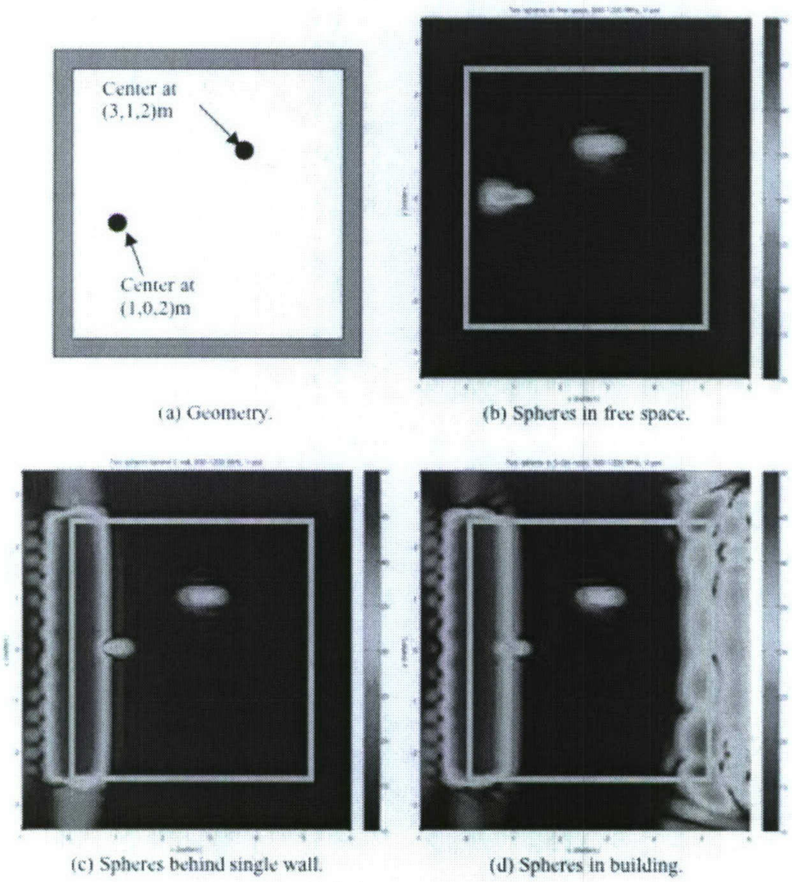


Figure 4. The first basic image study checks the process with target objects in free space, then builds up the scene complexity.

More thorough image analysis was undertaken of the basic scene as shown in figure 5.

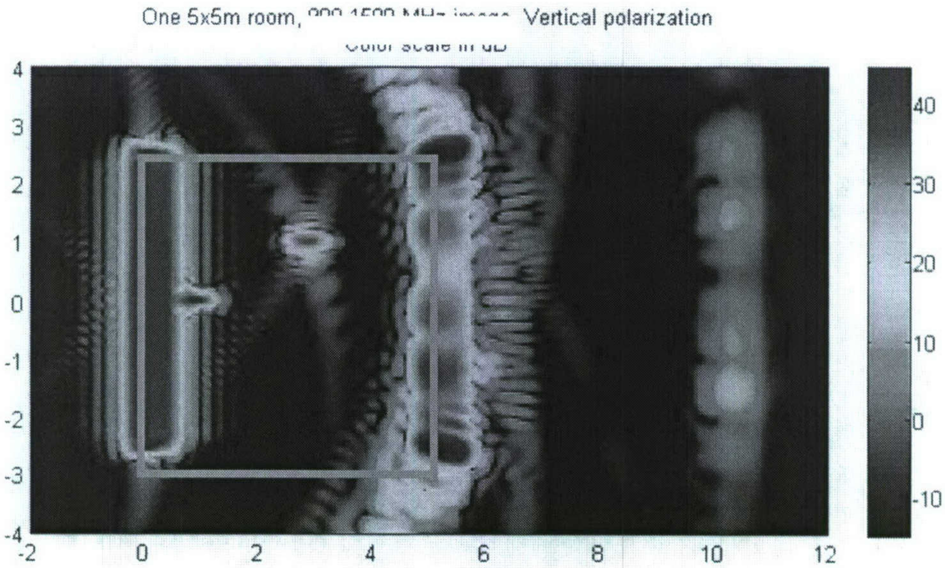
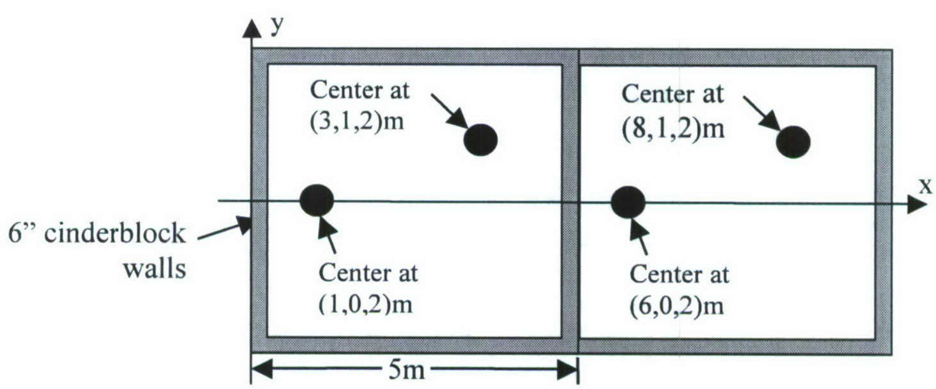
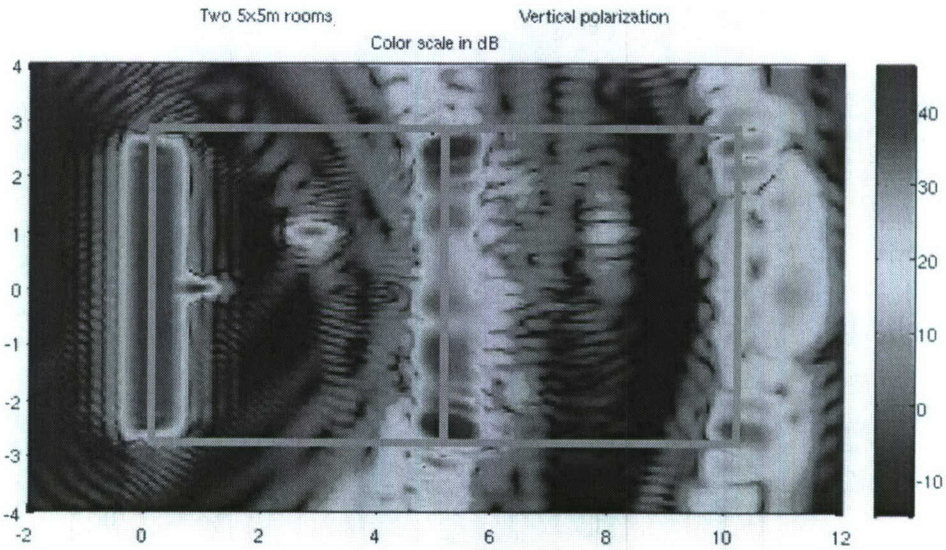


Figure 5. Two spheres in a single room with extended range image formation.

Radar data from more complex scenes (figure 6 a) were also generated and images formed from that data. In all the cases, the SAR is operated at a 5 meter standoff from the building front wall.



(a)



(b)

Figure 6. Scene geometry (a) and resulting image (b) for two spheres in each of two rooms. All of the walls are 6" thick cinder block. The sphere just inside the interior wall is difficult to notice in the image, and the most interior sphere near the middle of the back room is clearly present.

The azimuth beamwidths (in the y direction) used for radar data generation are the same as anticipated in the final radar design.

Images from the OSH radar data were also computed at SET, with slightly different weighting functions in azimuth and range, and slightly different image color mapping functions. Both of these detailed considerations influence the appearance of the image. These details will be refined and optimized in Phase II of the program to maximize the usefulness of the images toward the Random Radar mission of remotely locating enemy combatants inside of buildings.

Figure 7 shows the image SET made form the OSU radar data for the original one room with two sphere scene.

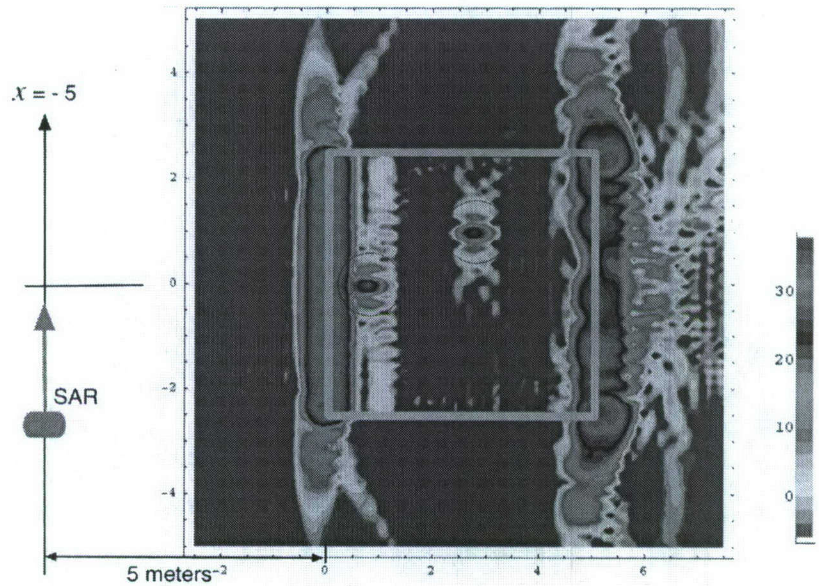


Figure 7. SAR image of 2 spheres inside a building from simulated data that was used in figure 4d. The two sphere responses have been circled. Comparison between this image and the image of 4d exemplifies the different result that may be obtained from the same data. This image more clearly defines the sphere near the front wall, but has significantly more artifacts than in figure 4d.

In addition to selection of weighting functions and color mapping schemes, the resolution of the image computation itself is influential on the ultimate image appearance.

The near field data that OSU produced for these scenes reflects the operations of the Random Radar, where data was generated as the radar moved by the scene in a straight line, resulting in $S_{nf}(u,r,\omega)$ where u is the radar position during the drive-by. The images shown in figures 4 through 7 were made by use of integration over frequency and range with the phase canceling factor e^{+jkr} hence :

$$I(x,y) = \left| \int_{y-L/2}^{y+L/2} \int_{\omega} e^{jkr} S_{nf}(u,r,\omega)\, w(\omega)\, d\omega\, du \right|^2 \qquad (1)$$

where the $w(\omega)$ term is a weighting function.[1]

SPECIAL CONSIDERATIONS FOR SHORT RANGE SAR

The unique mission of this SAR requires a departure from SAR signal processing methods using the far field assumption where the backscattered signals are essentially plane waves. All such approximations and signal processing development based on the far field approximation will not apply to the Random Radar mission, since the nearest targets are as little as a few meters away

[1] Burkholder et. al., "Model-based near field imaging of objects inside a room", submitted to the IEEE Antennas and Propagation conference, 2007.

from the radar. Consequently, the backscattered signal from a point target as a function of carrier frequency may be expressed as $S_{nf}(r,\omega) = A(\omega)\frac{e^{-jkr}}{r^2}$ where $k = \omega/c$, ω is (radian) frequency, c is the speed of light, $A(\omega)$ is the target amplitude vs. frequency, and r is the distance between the point target and the radar. The equation reflects the spherical wave-front nature of the backscattered signals as will occur in a short range mission.

WAVEFORM AND RADAR SYSTEM DESIGN

SYSTEM SIGNAL BLOCK DIAGRAMS

The following block diagrams are presented to provide a clearer understanding of the numerous factors in system design which are influenced by waveform selection. This material is an expansion of the waveform trade-off survey given in report #2. There, the waveform auto-correlation functions were discussed in detail. Here, each waveform which has been considered will be utilized on paper with the attendant block diagram to better illustrate the numerous interacting factors that arise from use of each waveform. The practicality of each waveform was surveyed briefly in table 3 of report #2.

SHORT PULSE WAVEFORM

A block diagram of a short pulse radar system is given in figure 8. The block diagram addresses the case of a pulsed RF carrier waveform but much of the discussion here applies to pulsed noise waveforms also.

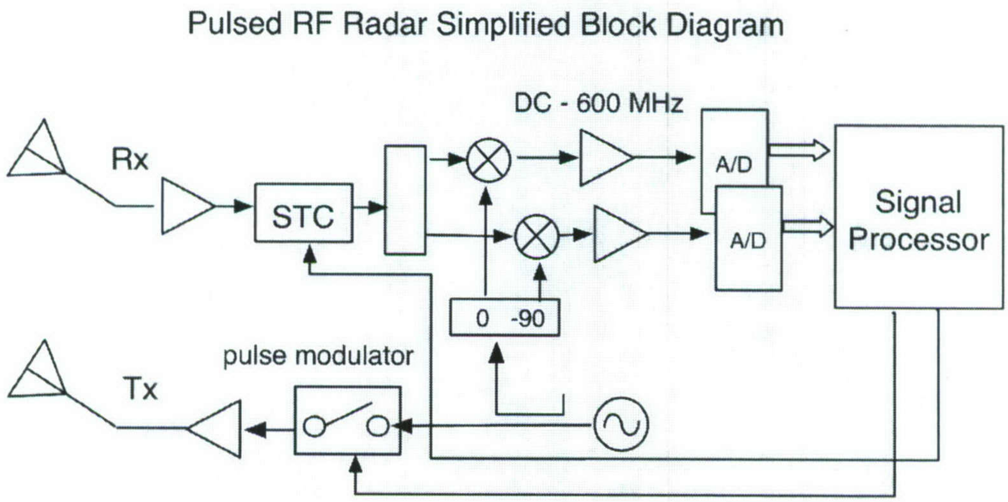


Figure 8. Simplified Block Diagram for a pulsed RF carrier type radar. Critical component technologies in this type of radar are the STC circuit, the A/Ds, and the pulse modulator.

For the Random Radar using this architecture, the A/Ds must operate at a high frequency sampling rate in a quadrature receiver to achieve adequate slant range resolution. The quadrature receiver introduces quadrature amplitude and phase errors which cannot be suppressed in practical terms beyond certain limits via calibration methods. Use of a single channel receiver in the Random Radar is all but precluded since a single A/D must operate at twice the quadrature sampling rate to correctly sample the single channel, and such sample rates are not readily available.

Pseudo Noise Coded Waveforms

Long duration waveforms using some form of high speed coding, either pseudo-noise or pure noise, may exhibit high range resolution if the coding bandwidth is adequate. A block diagram that implements coding via Bi-Phase Shift Keying (BPSK) is shown in figure 9.

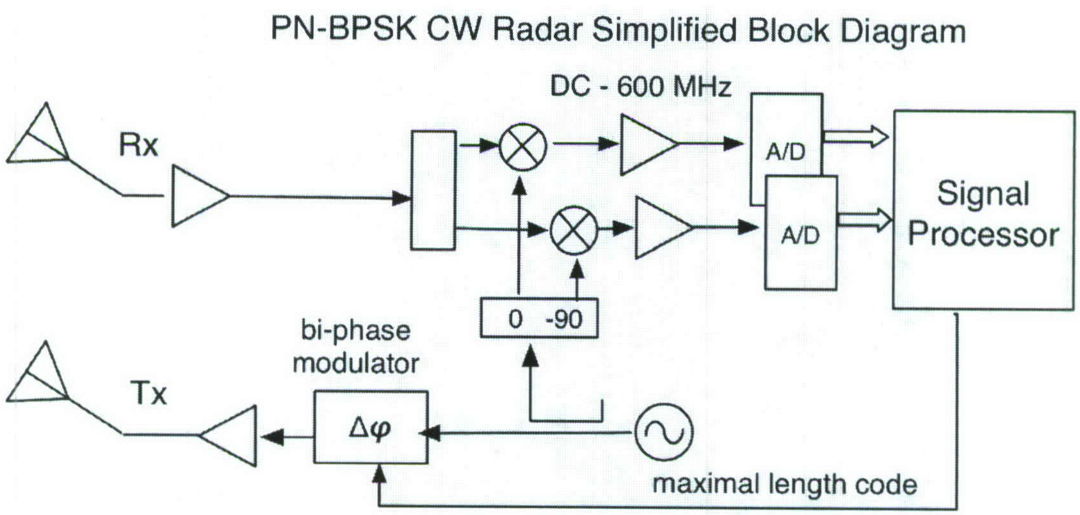


Figure 9. Continuous wave BPSK type radar. The range resolution is set by the code rate. This is one of the lowest cost methods to implement a high range resolution radar for applications that demand only limited dynamic range.

The auto correlation function ranging sidelobes of this type waveform are proportional to the code length; as an example, a code length of 8191 will exhibit a 78 dB ranging sidelobe level.

Pure Noise Coded Waveforms

The block diagram of a radar that uses pure noise waveforms in shown in figure 10. The noise is modulated onto an RF carrier via, phase, frequency, or amplitude modulation.

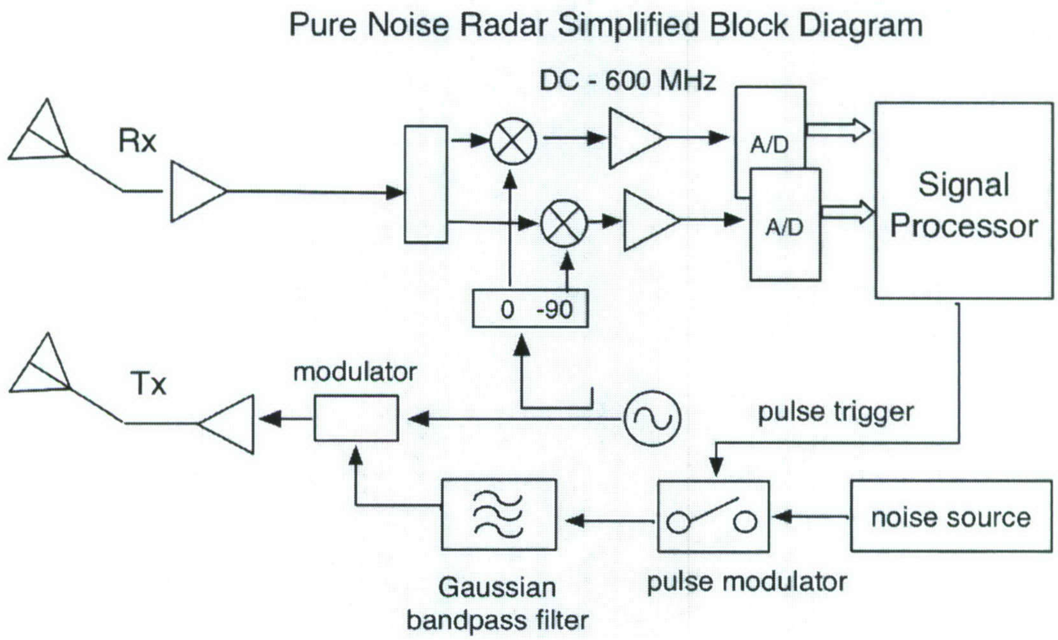


Figure 10. Noise waveform radar block diagram.

The pure noise radar system shown in figure 10 was studied at length during the program, where all the benefits and weaknesses of this design approach were identified.

STEPPED FREQUENCY WAVEFORM

A block diagram of a stepped frequency radar is shown in figure 11.

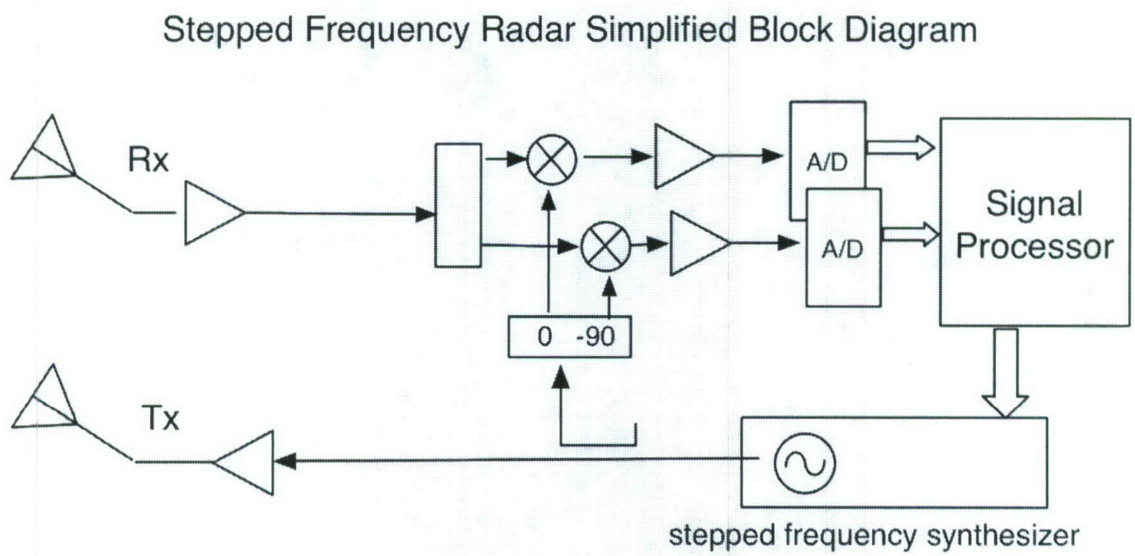


Figure 11. Stepped Frequency Radar Block Diagram. The radar operates by stepping the source frequency across the RF bandwidth.

The required ranging sidelobe level in the waveform's auto correlation function is achieved by weighting the complex baseband data with a window function prior to executing an FFT. This window function has a deleterious effect of widening the point target response of the system in time, thus reducing range resolution. Such resolution may be recovered by using relatively more RF bandwidth, however such required excess RF bandwidth can be substantial. For instance, in the case of using a weighting function adequate for the Random Radar application, a considerable amount of excess bandwidth will need to be used.